# Impact of Reduced Common Mode Voltage PWM and Common mode inductor on EMI Characteristics of an Inverter-Driven Motor

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#### Abstract

Pulse width modulation (PWM) inverters have been widely used in the variable-speed motor drive. However, the common mode voltage (CMV) and common mode current (CMC) produced by PWM inverters cause EMI to electronic equipments around. This paper experimentally investigates the CMV/CMC characteristics of important reduced CMV PWM methods, such as active zero state PWM1 (AZSPWM1), near state PWM (NSPWM) and three-dimension AZSPWM (3D-AZSPWM), for a two-level three-phase voltage source inverter, with and without a common mode inductance (CMI). Experimental results are helpful to the research of the EMI characteristics of the inverter-driven motor and suggest that a combined algorithm using 3D-AZSPWM and NSPWM with a CMI inserted makes a promising way to improve its EMI characteristics.

### 1. Introduction

Voltage source pulse width modulation (PWM) inverters have been widely applied in the variable-speed motor drive system for advantages such as low THD of output waveform, high power factor, high energy efficiency, etc. However, the common mode voltage (CMV) brings about common mode current (CMC, also known as leakage current) through the stray capacitors to the ground and produces conducted and radiated electromagnetic interference (EMI) to electronic equipments [1-3]. The conducted EMI may interfere with other electronic equipments through power lines, and the radiated EMI may bring malfunction to radio-controlled devices e.g., AM radio receivers, with a range from 100 kHz to several MHz [4].Those negative impacts become serious with the increase of switching frequency and power of electronic elements.

Conventional PWM methods, for example, 7-segment space vector PWM (7-SVPWM), have poor common mode EMI characteristics [5]. Recently various strategies have been proposed to solve the problem and the reduced CMV PWM (RCMV-PWM) methods or a common mode inductor (CMI, also known as the common mode choke) seems to be a promising approach with the availability and cost taken into consideration [2,4-5].

This paper experimentally investigates the performance of a two-level three-phase voltage source PWM inverter with a motor load for important RCMV-PWM methods, such as active zero state PWM1 (AZSPWM1) [6], near state PWM (NSPWM) [7] and three-dimension AZSPWM (3D-AZSPWM) [8]. Besides, their impact on EMI is evaluated with and without CMIs .Experimental results show that NSPWM and 3D-AZSPWM have good CMV/CMC characteristics and the CMI has a dramatic effect on suppressing the CMC peak. It suggests that a combined algorithm using those two methods with a CMI inserted makes a promising way to improve the EMI characteristics of the inverter-driven motor.

# 2. RCMV-PWM Methods

In space vector modulation methods for two-level three-phase inverters, there are six non-zero vectors whose output CMV is  $\pm V_{dc}/6$  and two zero vectors corresponding to  $\pm V_{dc}/2$ . The essence of RCMV-PWM methods is to substitute the non-zero vectors for zero vectors when tracing the reference voltage( $V_{ref}$ ). According to the principle, various RCMV-PWM methods, which theoretically limit the CMV to  $\pm V_{dc}/6$ , have been developed. However, since the simultaneous switching requirement is too difficult to be satisfied in practice, only AZSPWM1, NSPWM and 3D-AZSPWM are practically feasible [5]. Therefore, this paper will mainly focus on those methods. As for comparison, conventional 7-SVPWM is also utilized.

Compared with 7-SVPWM (shown in Fig.1.(a)), AZSPWM1 utilizes two adjacent vectors and two opposite vectors with equal duration time. The selection of those two opposite active vectors depends on the location of  $V_{ref}$ . A simple illustration of AZSPWM1 is displayed in Fig.1.(b). As for NSPWM, type B  $\alpha\beta$  plane [7] is used. This method employs only three adjacent vectors and sequences them to obtain the minimum switching count. Thus, one phase is not switched during each PWM cycle as shown in Fig.1.(c). In Fig.1.(d), the non-zero vectors utilized and switching sequence of 3D-AZSPWM are the same as those of AZSPWM1. However, unlike ordinary RCMV-PWM methods which only focus on the projections of  $V_{ref}$  onto the  $\alpha\beta$  plane, this method aims

to let the average value of the zero sequence projection component of  $V_{ref}$  on the  $\alpha\beta0$  plane equal to zero. The mathematical constraint equations of 3D-AZSPWM are very different, as shown in equation (1) and the duration time of each vector is given in equation (2). The modulation ratio (*M*) ranges from 0 to 0.91 for 7- SVPWM and AZSPWM1, 0.61~0.91 for NSPWM and 0~0.78 for 3D-AZSPWM [6, 8].

$$\begin{cases} V_{1\alpha}T_{1} + V_{2\alpha}T_{2} + V_{3\alpha}T_{3} + V_{6\alpha}T_{6} = V_{ref\alpha}T_{s} \\ V_{1\beta}T_{1} + V_{2\beta}T_{2} + V_{3\beta}T_{3} + V_{6\beta}T_{6} = V_{ref\beta}T_{s} \\ V_{10}T_{1} + V_{20}T_{2} + V_{30}T_{3} + V_{60}T_{6} = V_{0}T_{s} \\ T_{1} + T_{2} + T_{3} + T_{6} = T_{s} \\ \end{cases}$$
(1)  
$$\begin{cases} T_{1} = V_{ref}T_{s}\cos\theta / V_{dc} \\ T_{2} = V_{ref}T_{s}(\cos\theta + \sqrt{3}\sin\theta) / 2V_{dc} \\ T_{3} = T_{s} / 2 - V_{ref}T_{s}\cos\theta / V_{dc} \\ T_{6} = T_{s} / 2 - V_{ref}T_{s}(\cos\theta + \sqrt{3}\sin\theta) / 2V_{dc} \end{cases}$$
(2)



(a) 7-SVPWM in region A1, (b) AZSPWM1 in region A1 (c) NSPWM in region B1, (d) 3D-AZSPWM in region A1

# 3. Common Mode Inductor

EMI noise generated by CMC of PWM inverters is primarily several times the fundamental frequency, plus higher harmonics. To provide proper attenuation, the impedance of the common mode circuit must be sufficiently high over this frequency range. The CMI, which has high impedance over a wide high frequency range, is a cost-effective passive hardware to suppress CMC [9]. A three-phase CMI is usually made by a ferrite toroid core with three symmetrical windings and its material and size depend on the parameters of current, impedance and frequency. The CMI is inserted between the outputs of the inverter and the inputs of the motor as shown in Fig.2.The Inductance value of the CMI is typically a few mH and the equivalent common mode capacitance of CMI is more dominant than the motor common mode impedance and the simplified equivalent common mode circuit is displayed in Fig.3.  $L_{\rm cm}$  is the inductance of the CMI and  $C_{\rm s}$  is the equivalent lumped capacitance inside the motor and between the motor neutral point and DC-link. In our work, a small CMI with 1.13mH tested at the frequency of 10 kHz has been utilized in the induction motor drive.



Fig.2. System of an inverter-driven motor

Fig.3. Simplified equivalent common mode circuit [4]

### 4. Experiments and Analyses

In this paper, the CMV/CMC performance of a two-level three-phase inverter driving a squirrel-cage motor under no-load state is experimentally evaluated with and without the CMI. PWM methods such as 7-SVPWM, AZSPWM1, NSPWM and 3D-AZSPWM are realized in a dual-DSP control platform and the fundamental switching frequency is set to be 6.4 kHz. As shown in Fig.2, the isolation transformer is fed form the 220 V (phase) and 50Hz power grid and the DC-link keeps at 510V.With the neutral point of the transformer connected to the chassis of the motor through a long cable, the CMC is correctly measured via a current transducer. The CMV is calculated by measuring voltages of three phases between the motor and the mid-point of DC-link. Experimental results are listed in Tab.1 and Fig.4 gives the waveforms of CMV/CMC for four PWM methods under M=0.65 without CMI.

<b>Modulation ratio</b>		M=0.4				M=0.65				M=0.8			
EMI filter type	EMI noise & PWM methods	CMV-Peak (V)	CMV-RMS (V)	CMC-Peak (mA)	CMC- RMS (mA)	CMV-Peak (V)	CMV-RMS (V)	CMC-Peak (mA)	CMC- RMS (mA)	CMV-Peak (V)	CMV-RMS (V)	CMC-Peak (mA)	CMC- RMS (mA)
Without CMI	7-SVPWM	255	200	450	78	266	175	440	79	262	130	453	75
	AZSPWM1	254	83	446	72	254	84	380	75	251	83	423	73
	NSPWM	/	/	/	/	93	85	390	60	88	83	303	59
	3D-AZSPWM	93	84	290	68	91	83	273	67	/	/	/	/
With CMI	7-SVPWM	309	199	286	65	313	161	313	66	307	130	270	66
	AZSPWM1	234	84	213	56	229	84	240	62	241	85	226	63
	NSPWM	/	/	/	/	138	84	243	56	126	84	190	54
	<b>3D-AZSPWM</b>	134	86	247	60	134	85	235	60	/	/	/	/

Tab.1. Comparison of the CMV/CMC performance of four PWM methods with and without CMI



Fig.4. Waveforms of CMV/CMC for four PWM methods under M=0.65 without CMI

As for CMV, RCMV-PWM methods have a good performance in reducing its peak and RMS value, which can be seen from the first four lines. However, for AZSPWM1, some unexpected voltage spikes come out at the instant when the function time of no-zero space vector is smaller than the dead-time, as shown in Fig.4.(b). From the aspect of CMC, the peak value is reduced by nearly 33%~35% and the RMS value is reduced by 12%~21% by adopting NSPWM and 3D-AZSPWM, compared with 7-SVPWM. However, experimental results show that AZSPWM1 has a poor effect on CMC and this may be caused by the dead-time effect. Also, the performance of NSPWM at higher modulation ratio (M=0.8) is better than that at low one (M=0.65). In the inverter-driven motor system, since the common mode voltage base frequency is far less than the resonant frequency of common mode circuit, the peak value of CMC is more dependent on the *dv/dt* of the CMV, and less dependent on the magnitude and wave shape of the CMV. Compare the last four lines with the first ones, it is found that the CMI has little importance to the CMV and it may bring oscillation to the common mode circuit if the inductance value is not proper. The peak value of CMC is dramatically reduced with the CMI inserted and the reduction of RMS value of CMC is not obvious as a result of the low resistance of CMI. Those conclusions suggest that a combined algorithm using 3D-AZSPWM and NSPWM with a CMI inserted makes a promising way to improve its EMI characteristics of the inverter-driven motor.

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